Examination of the Endogeneity Between Macroeconomic Performance and Public Health Outcomes in Closed and Open-Economy Models

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Abstract

As nations grapple with resource allocation decisions that simultaneously affect economic growth and population health, the complex relationship between macroeconomic performance and public health outcomes has emerged as a critical area of inquiry in contemporary economic research, particularly. This paper examines the endogenous relationship between macroeconomic indicators and public health metrics through the lens of both closed and open-economy models, utilizing advanced mathematical frameworks to capture the bidirectional causality inherent in these systems. We develop a comprehensive theoretical model that incorporates feedback mechanisms between health capital formation, productivity growth, and aggregate economic performance, while accounting for international trade effects and capital mobility constraints. Our analysis reveals significant heterogeneity in the strength and direction of these relationships across different economic structures, with open economies demonstrating greater volatility but also enhanced adaptive capacity through external market integration. The findings suggest that traditional macroeconomic policy instruments may produce substantially different health outcomes depending on the degree of economic openness, with implications for optimal policy design in an increasingly interconnected global economy. We demonstrate that endogeneity bias in conventional estimation approaches can lead to systematic underestimation of the true causal effects, necessitating more sophisticated econometric methodologies. The research contributes to the growing literature on health economics by providing a unified theoretical framework that reconciles apparent contradictions in empirical findings across different country contexts and time periods.

1 Introduction

The relationship between macroeconomic performance and public health outcomes represents one of the most compelling yet challenging areas of economic research in the modern era [1]. As governments worldwide face increasingly complex trade-offs between economic growth objectives and health system investments, understanding the fundamental mechanisms that govern these interactions has become paramount for effective policy formulation. The traditional view of health as merely a consumption good has given way to a more nuanced understanding of health as both an input to and output of the economic production process, creating a web of interdependencies that challenge conventional analytical frameworks.

The significance of this relationship has been amplified by recent global events that have demonstrated the profound economic consequences of health crises, while simultaneously revealing how economic conditions can rapidly translate into health outcomes across populations. The COVID-19 pandemic, in particular, has highlighted the bidirectional nature of health-economy interactions, showing how health shocks can trigger massive economic disruptions, while economic vulnerabilities can exacerbate health disparities and limit public health response capabilities. [2]

This paper addresses a critical gap in the existing literature by developing a comprehensive theoretical framework that explicitly accounts for the endogenous nature of the relationship between macroeconomic performance and public health outcomes. While previous research has often treated these variables as exogenously determined or has focused on unidirectional causal relationships, our approach recognizes that health and economic outcomes are simultaneously determined through complex feedback mechanisms that operate across multiple time horizons and spatial scales.

Our analysis distinguishes between closed and open-economy contexts, recognizing that the degree of international economic integration fundamentally alters the transmission mechanisms through which health and economic shocks propagate. In closed economies, these relationships operate primarily through domestic channels, with limited ability to smooth shocks through external markets [3]. Conversely, open economies benefit from access to international capital markets, technology transfer, and risk-sharing mechanisms, but also face greater exposure to external volatility and contagion effects.

The methodological approach employed in this study combines advanced mathematical modeling techniques with sophisticated econometric methods designed to address the endogeneity problems that have plagued previous empirical work in this area. We develop a dynamic stochastic general equilibrium model that incorporates health capital as both a stock variable that affects individual productivity and a flow variable that responds to economic conditions and policy interventions.

Our theoretical framework builds upon the seminal contributions of human capital theory while extending these insights to incorporate the specific characteristics of health investments that distinguish them from other forms of capital accumulation. Unlike physical or educational capital, health capital exhibits unique depreciation patterns, experiences threshold effects, and generates significant externalities that create market failures requiring government intervention. [4]

The paper proceeds to examine how these theoretical relationships manifest differently across closed and open-economy settings, with particular attention to the role of international trade, capital mobility, and technology diffusion in mediating health-economy interactions. We demonstrate that the welfare implications of various policy interventions depend critically on the degree of economic openness, with important implications for the design of optimal policy packages.

2 The endogenous growth literature Context

Unlike conventional forms of capital, health capital cannot be separated from the individual, exhibits non-linear depreciation patterns, and generates significant spillover effects that create important externalities in both production and consumption. [5]

Table 1: Endogenous Growth, Health Capital, and Economic Openness

Dimension	**Closed Economies**	**Open Economies**	**Common Growth Channels**	**Institutional Role**
Health Investment Constraints	Bound by domestic savings	Access to external financing via capital markets	Human capital deepening	Enables counter-cyclical spending
Shock Transmission	Internal only, lower volatility	External contagion via trade, finance	Productivity and labor supply	Buffers external shocks
Disease Profile	Infectious disease burden dominates	Shift toward NCDs and chronic illness	Cognitive and physical performance	Guides resource allocation
Trade Effects	Limited access to technology	Enhanced access to medicines, tech transfer	Sectoral innovation, spillovers	Regulates import dependency
Labor Mobility	Static workforce, domestic training	Brain drain and return migration dynamics	Skill transfer, remittance flows	Manages workforce capacity
Financial System	Shallow capital markets, low health insurance penetration	Deep markets, private financing available	Savings mobilization, risk pooling	Stabilizes investment flows

The endogenous growth literature has long recognized the potential for health improvements to drive sustained economic growth through multiple channels. Enhanced health status increases individual productivity by reducing absenteeism, improving cognitive function, and extending working lifespans. At the aggregate level, healthier populations demonstrate higher savings rates, greater innovation capacity, and more efficient resource allocation across sectors. These effects are particularly pronounced in developing economies where the burden of preventable diseases imposes substantial constraints on economic development.

However, the relationship between health and economic performance is not unidirectional [6]. Economic conditions fundamentally determine the resources available for health investments, both through private spending on

health goods and services and through public sector capacity to provide health infrastructure and services. Economic volatility can undermine health outcomes through multiple pathways, including reduced access to healthcare, deterioration in nutrition and living conditions, and increased stress-related health problems.

The distinction between closed and open economies introduces additional complexity to these relationships. In closed economies, health-economy interactions operate primarily through domestic channels, with limited ability to smooth shocks or access external resources during health crises [7]. The domestic savings constraint binds more tightly, potentially limiting the scope for health investments during economic downturns when such investments may be most needed.

Open economies face a different set of trade-offs and opportunities. Access to international capital markets can provide crucial financing for health investments during economic crises, while technology transfer and knowledge spillovers can accelerate health improvements. However, economic openness also introduces new sources of volatility and contagion, as external shocks can rapidly transmit through trade and financial channels to affect domestic health outcomes.

The epidemiological transition that accompanies economic development further complicates these relationships [8]. As economies develop and integrate into global markets, disease patterns shift from predominantly infectious diseases toward chronic non-communicable diseases. This transition alters the economic costs and benefits of different health interventions and changes the optimal allocation of health resources across prevention and treatment activities.

International trade introduces additional pathways through which health and economic outcomes interact. Trade in health goods and services can improve access to essential medicines and medical technologies, but may also create dependencies that become problematic during supply chain disruptions [9]. Environmental health effects of increased industrial production and transportation can create negative health externalities that offset some of the economic benefits of trade expansion.

Labor mobility adds another dimension to these interactions in open economies. Brain drain of health professionals can undermine domestic health system capacity while potentially generating remittance flows that support health investments in origin countries. Similarly, return migration can facilitate technology transfer and skill upgrading that benefits both health and economic outcomes. [10]

The role of institutions emerges as a critical mediating factor in these relationships. Strong institutional frameworks can help countries capture the benefits of economic openness while mitigating the associated risks to public health. Effective regulatory systems, robust social safety nets, and competent public health infrastructure enable countries to maintain health outcomes even during periods of economic volatility.

Financial market development plays a particularly important role in mediating health-economy interactions. Deep financial markets can facilitate private health investments and provide insurance mechanisms that protect households from health-related financial shocks [11]. However, financial market volatility can also create procyclical effects that amplify the health consequences of economic downturns.

3 Mathematical Modeling

The mathematical foundation for analyzing the endogenous relationship between macroeconomic performance and public health outcomes requires a sophisticated dynamic framework that captures the simultaneous determination of health and economic variables while accounting for the structural differences between closed and open economies. We begin by establishing a general equilibrium model that incorporates health capital as both a production input and a utility argument.

Consider a representative agent economy where individual utility at time t is given by $U_t = \ln(C_t) + \beta \ln(H_t)$, where C_t represents consumption and H_t represents health capital [12]. The parameter $\beta > 0$ captures the relative importance of health in the utility function. The agent faces a budget constraint $C_t + I_{H,t} + I_{K,t} = Y_t$, where $I_{H,t}$ and $I_{K,t}$ represent investments in health and physical capital respectively, and Y_t is total income.

The production function takes the form $Y_t = A_t K_t^{\alpha} (H_t L_t)^{1-\alpha}$, where A_t represents total factor productivity, K_t is physical capital, L_t is labor supply, and H_t serves as an efficiency parameter that enhances effective labor input. This specification captures the dual role of health as both a direct utility argument and a productivity enhancer.

Health capital evolves according to the accumulation equation $H_{t+1} = (1 - \delta_H(H_t))H_t + \phi(I_{H,t}, G_{H,t}, E_t)$, where $\delta_H(H_t)$ represents the health depreciation rate that depends on current health status, $G_{H,t}$ denotes public health expenditures, and E_t captures environmental factors that affect health. The investment efficiency function $\phi(\cdot)$ exhibits decreasing returns to scale and positive cross-partial derivatives, reflecting complementarities between private and public health investments.

The depreciation function $\delta_H(H_t)$ follows a non-linear specification $\delta_H(H_t) = \delta_0 + \delta_1 H_t^{-\gamma}$, where $\gamma > 0$ captures the threshold effects in health depreciation. This formulation reflects the empirical observation that individuals

with better baseline health experience lower rates of health deterioration, creating path-dependent dynamics that can lead to health inequality persistence.

For the closed economy case, the resource constraint becomes $C_t + I_{K,t} + I_{H,t} + G_t = Y_t$, where G_t represents total government expenditure. The government budget constraint is $G_t = \tau_t Y_t + B_{t+1} - (1 + r_t)B_t$, where τ_t is the tax rate, B_t is government debt, and r_t is the interest rate determined by domestic savings-investment balance.

The interest rate in the closed economy satisfies the equilibrium condition $S_t = I_{K,t} + I_{H,t} + \Delta B_t$, where savings $S_t = Y_t - C_t - \tau_t Y_t$ must equal total investment demand. This constraint implies that increases in health investment must be financed through either reduced consumption, lower physical capital investment, or higher government borrowing, creating important trade-offs in resource allocation. [13]

For the open economy specification, we introduce external sector interactions through the current account identity $CA_t = X_t - M_t + NFA_t r_t^*$, where X_t and M_t represent exports and imports, NFA_t is net foreign assets, and r_t^* is the world interest rate. The domestic interest rate in the open economy converges to $r_t^* + \rho_t$, where ρ_t represents a country risk premium that depends on macroeconomic fundamentals and institutional quality.

International trade in health goods introduces additional complexity through the specification $M_{H,t} = \mu_0 + \mu_1(H_t^* - H_t) + \mu_2 Y_t$, where $M_{H,t}$ represents health-related imports and H_t^* is the global health frontier. This specification captures both income effects and technology gap effects in health trade patterns.

The technology diffusion process in open economies follows $A_{t+1} = (1 - \delta_A)A_t + \theta_1 R\&D_t + \theta_2 TO_t(A_t^* - A_t)$, where TO_t measures trade openness, A_t^* is the global technology frontier, and the parameters θ_1 and θ_2 govern domestic innovation and technology absorption respectively. Health capital affects both innovation capacity and absorption ability through the term $\theta_1 = \theta_{1,0} H_t^{\eta_1}$ and $\theta_2 = \theta_{2,0} H_t^{\eta_2}$.

The stochastic elements of the model are captured through shock processes for productivity, health, and external conditions [14]. Productivity shocks follow $\ln A_{t+1} = \rho_A \ln A_t + \epsilon_{A,t+1}$, while health shocks affect both the depreciation rate and investment efficiency through $\delta_{H,t} = \delta_H + \sigma_\delta \epsilon_{\delta,t}$ and $\phi_t = \phi + \sigma_\phi \epsilon_{\phi,t}$.

The government's health policy response function takes the form $G_{H,t} = g_0 + g_1 H_t + g_2(H_t^* - H_t) + g_3 Y_t + g_4 \epsilon_{H,t-1}$, where the parameters capture the responsiveness of public health spending to health status, health gaps, income levels, and lagged health shocks. This specification allows for both automatic stabilizer effects and discretionary policy responses.

The equilibrium system consists of the first-order conditions for the representative agent's optimization problem, the government budget constraint, market clearing conditions, and the law of motion for state variables. The Euler equations for consumption and health investment are:

$\frac{1}{C_t} = \beta E_t[\frac{1}{C_{t+1}}(1 + r_{t+1})]$

$\frac{\phi_H(I_{H,t}, G_{H,t}, E_t)}{C_t} = \beta E_t[\frac{1}{C_{t+1}}((1 - \alpha)\frac{Y_{t+1}}{H_{t+1}} + (1 - \delta_H(H_{t+1})) + \beta \frac{1}{H_{t+1}})]$

These conditions reveal the key trade-offs in health investment decisions and demonstrate how health capital affects both future productivity and direct utility. The second equation shows that optimal health investment equates the marginal cost of health investment to the present value of future benefits, which include productivity gains, reduced depreciation, and direct utility effects. [15]

4 Empirical Methodology and Econometric Challenges

The empirical analysis of endogenous relationships between macroeconomic performance and public health outcomes presents significant methodological challenges that require sophisticated econometric approaches to address issues of simultaneity, omitted variable bias, and measurement error. The simultaneous determination of health and economic outcomes creates identification problems that cannot be resolved through conventional regression techniques, necessitating the use of instrumental variable methods, panel data techniques, and structural estimation approaches.

The fundamental identification challenge arises from the fact that health outcomes affect economic performance through productivity channels, while economic conditions simultaneously determine the resources available for health investments and the environmental factors that influence health outcomes. This bidirectional causality creates a classic simultaneity problem where ordinary least squares estimation will yield biased and inconsistent parameter estimates. [16]

To address these challenges, we employ a multi-pronged empirical strategy that combines reduced-form estimation with structural modeling approaches. The reduced-form analysis utilizes instrumental variable techniques based on exogenous variation in health and economic conditions, while the structural approach estimates the parameters of the theoretical model developed in the previous section using generalized method of moments and maximum likelihood techniques.

The instrumental variable strategy exploits several sources of exogenous variation in health and economic outcomes. For health outcomes, we utilize geographic and climatic variables that affect disease transmission and health conditions but do not directly influence economic performance through other channels [17]. These

instruments include measures of temperature variability, precipitation patterns, elevation, and distance from disease vectors, all of which have been shown to have strong predictive power for health outcomes while satisfying the exclusion restriction for economic outcomes.

For economic performance, we employ external demand shocks based on trading partner growth rates, world commodity price movements, and international financial market conditions. These instruments provide exogenous variation in domestic economic conditions that is uncorrelated with domestic health policies or unobserved factors that might affect both health and economic outcomes simultaneously.

The panel data specification takes the form:

$Health_{i,t} = \alpha_1 + \beta_1 Economy_{i,t} + \gamma_1 X_{i,t} + \delta_1 Z_{i,t} + \mu_i + \lambda_t + \epsilon_{i,t}$

$Economy_{i,t} = \alpha_2 + \beta_2 Health_{i,t} + \gamma_2 X_{i,t} + \delta_2 W_{i,t} + \mu_i + \lambda_t + \nu_{i,t}$

where $Health_{i,t}$ and $Economy_{i,t}$ represent vectors of health and economic outcome variables for country i in period t, $X_{i,t}$ contains control variables that affect both outcomes, $Z_{i,t}$ and $W_{i,t}$ are vectors of instruments for economic and health outcomes respectively, μ_i and λ_t represent country and time fixed effects, and $\epsilon_{i,t}$ and $\nu_{i,t}$ are error terms.

The identification strategy requires that the instruments satisfy both relevance and exclusion restrictions [18]. Relevance is tested through first-stage F-statistics and partial R-squared measures, while exclusion restrictions are evaluated through overidentification tests and economic reasoning about the plausibility of direct effects on the outcome variables.

To account for the dynamic nature of health-economy interactions, we extend the basic specification to include lagged dependent variables and employ dynamic panel data techniques. The Arellano-Bond and Blundell-Bond estimators are used to address the correlation between lagged dependent variables and individual fixed effects, while controlling for potential endogeneity in other explanatory variables.

The structural estimation approach directly estimates the parameters of the theoretical model using simulated method of moments techniques [19]. The model is solved numerically to generate artificial data that is then matched to observed moments from the actual data. This approach allows us to recover the deep structural parameters that govern health-economy interactions and to conduct counterfactual policy experiments.

The moment matching procedure targets key statistics that capture the essential features of health-economy relationships, including correlations between health and economic outcomes, persistence in both variables, volatility measures, and cross-country differences in these relationships. The objective function minimizes the weighted distance between theoretical and empirical moments:

$J(\theta) = [m_N - m_S(\theta)]' W [m_N - m_S(\theta)]$ [20]

where m_N represents empirical moments, $m_S(\theta)$ are simulated moments from the theoretical model evaluated at parameter vector θ, and W is a weighting matrix.

The estimation procedure involves several stages. First, we calibrate some parameters using external information from previous studies and institutional data. Second, we estimate the remaining parameters by minimizing the objective function [21]. Third, we conduct sensitivity analysis to assess the robustness of results to alternative calibration choices and moment selection.

Special attention is given to addressing measurement error issues that are particularly severe in health outcome data. Classical measurement error in dependent variables does not bias coefficient estimates but reduces precision, while measurement error in explanatory variables creates attenuation bias that can lead to underestimation of true causal effects. We employ multiple indicator approaches and use reliability ratios from validation studies to correct for measurement error bias.

The heterogeneity between closed and open economies is addressed through several approaches [22]. First, we estimate separate models for countries with different degrees of economic openness, using measures of trade openness, capital account openness, and financial market development to classify countries. Second, we include interaction terms between openness measures and key explanatory variables to test for differential effects. Third, we conduct subsample analysis and rolling regressions to examine how relationships change as countries become more integrated into the global economy.

Robustness checks include alternative instrument sets, different estimation methods, varying sample periods, and sensitivity analysis for outlier observations [23]. We also conduct placebo tests using variables that should not be related to our instruments to verify that we are not capturing spurious relationships.

The temporal dimension of health-economy interactions requires careful modeling of distributed lag effects and potential regime changes. We employ flexible lag structures and test for structural breaks in the relationships over time. The possibility of threshold effects and non-linear relationships is explored through regime-switching models and smooth transition specifications. [24]

Table 2: Comparative Dynamics of Closed vs. Open Economies in Health-Economy Interactions

Dimension	**Closed Economies**	**Open Economies**	**Comparative Implication**	**Institutional Role**
Health Financing Constraint	Bound by domestic savings	Access to external capital	Greater fiscal flexibility under openness	Enables countercyclical health spending
Crisis Feedback Loop	Strong procyclicality, poverty-health traps	Smoothing via external resources	Openness dampens negative spirals	Coordination of fiscal and health policy
Technology	Limited access to advanced medical tech	Tech transfer, health imports	Improved care quality in open systems	Regulate trade dependencies
Knowledge Spillovers	Domestic-only practices	Global best practices diffusion	Enhances efficiency, innovation	Adopt evidence-based protocols
Health Risks from Globalization	Contained exposure	Disease transmission, environmental externalities	Trade-off between access and risk	Risk mitigation, surveillance systems
Volatility Exposure	Endogenous volatility only	Exposed to global market shocks	Greater health risk from financial contagion	Financial market oversight
Health-Economy Correlation	High and persistent	Weaker short-term, strong long-term	Dynamics differ, fundamentals persist	Buffer short-run shocks, sustain long-run goals
Labor Mobility	Static workforce, lower brain drain	Brain drain and remittances	Mixed effect on capacity and funding	HR planning, diaspora engagement
Exchange Rate Impact	Not applicable or minor	Alters cost of imported health goods	Input price sensitivity in open systems	Pricing regulation, strategic reserves

5 Comparative Analysis of Closed versus Open Economy Dynamics

The structural differences between closed and open economies create fundamentally distinct patterns in the relationship between macroeconomic performance and public health outcomes, with important implications for both the magnitude and persistence of these interactions. Our analysis reveals that economic openness operates as a critical mediating factor that alters the transmission mechanisms, volatility patterns, and policy effectiveness in health-economy relationships.

In closed economies, the constraints imposed by domestic resource availability create tighter linkages between health and economic outcomes, as countries must rely exclusively on internal resources to finance health investments and cope with health shocks. The binding nature of the domestic savings constraint means that health investments must compete directly with physical capital accumulation and consumption, creating more pronounced trade-offs during periods of economic stress. This resource constraint effect is particularly evident during economic downturns, when the opportunity cost of health spending rises precisely when health needs may be greatest due to deteriorating living conditions and reduced access to healthcare. [25]

The absence of external financing options in closed economies amplifies the procyclical nature of health spending, creating potentially destabilizing feedback loops during economic crises. When economic performance deteriorates, both private and public resources available for health investment decline, leading to further deterioration in health

outcomes that subsequently undermines productivity and economic recovery. This dynamic can create poverty-health traps where countries become locked into low-level equilibria characterized by poor health outcomes and weak economic performance.

Conversely, open economies benefit from access to international capital markets that can provide countercyclical financing for health investments during economic downturns [26]. The availability of external financing relaxes the domestic resource constraint and allows countries to maintain or even increase health spending during recessions, potentially breaking the negative feedback loops that characterize closed economies. However, this advantage comes with the cost of increased exposure to external volatility and the risk of sudden stops in capital flows during global financial crises.

The technology transfer mechanisms available to open economies create additional channels through which health outcomes can improve independently of domestic economic conditions. Access to international markets for health goods and services, medical technologies, and pharmaceutical products allows open economies to achieve health improvements that would be impossible to attain through domestic production alone. This effect is particularly pronounced for small economies that lack the scale to support domestic production of specialized medical equipment and pharmaceuticals. [27]

International trade also facilitates knowledge spillovers in health-related technologies and practices, allowing open economies to benefit from global advances in medical science and public health policy. The diffusion of best practices in disease prevention, treatment protocols, and health system organization can generate substantial health improvements that translate into productivity gains and economic growth. These spillover effects create positive externalities that may justify policies to promote economic openness from a public health perspective.

However, economic openness also introduces new sources of health risk through increased exposure to global disease transmission, environmental degradation from industrial production for export markets, and social disruption from rapid economic change [28]. The epidemiological consequences of globalization include accelerated spread of infectious diseases, increased prevalence of lifestyle-related chronic diseases, and potential widening of health inequalities between internationally integrated and isolated populations.

The volatility implications of openness create complex trade-offs for health outcomes. While access to international markets can help smooth domestic shocks, integration with global markets also exposes domestic economies to external volatility that can have significant health consequences. Financial market volatility can create boom-bust cycles that alternately improve and deteriorate health outcomes, while trade shocks can disrupt local production patterns and employment with direct implications for population health.

Our empirical analysis reveals that the correlation between health and economic outcomes is systematically lower in open economies, reflecting the greater availability of mechanisms to smooth shocks and decouple short-term economic fluctuations from health trends [29]. However, the long-term relationship between health and economic development remains strong in both contexts, suggesting that openness affects the dynamics rather than the fundamental nature of these relationships.

The policy implications of these differences are substantial. In closed economies, health policy must be more closely coordinated with macroeconomic policy due to the tighter resource constraints and stronger feedback effects. Countercyclical health spending policies may be difficult to implement without external financing, making prevention and health system efficiency crucial for maintaining health outcomes during economic downturns. [30]

For open economies, the greater policy flexibility provided by access to external resources must be balanced against the risks of external dependence and volatility. The optimal degree of openness from a health perspective may differ from the economically optimal level, creating potential tensions in policy design. Countries may need to develop stronger domestic health system capacity even while benefiting from international integration to ensure resilience against external shocks.

The role of institutions becomes particularly critical in mediating the health effects of economic openness [31]. Strong regulatory frameworks can help countries capture the benefits of international integration while mitigating the associated health risks. Effective social safety nets can protect vulnerable populations from the adverse health effects of increased economic volatility, while robust public health systems can manage the disease transmission risks associated with increased international connectivity.

Exchange rate dynamics in open economies create additional complexity in health-economy relationships through their effects on the relative prices of traded and non-traded health goods and services. Currency depreciation can increase the domestic cost of imported medicines and medical equipment while potentially improving the competitiveness of health tourism and medical services exports. These relative price effects can significantly alter the cost-effectiveness of different health interventions and the optimal allocation of health resources. [32]

The labor mobility dimension of economic openness introduces further complexity through brain drain effects in the health sector. The emigration of health professionals can undermine domestic health system capacity, while remittances from emigrants may provide resources for health investments. The net effect depends on the relative magnitudes of these competing forces and the ability of domestic institutions to train replacement health workers and efficiently utilize remittance flows.

6 Policy and Welfare Analysis

The endogenous relationship between macroeconomic performance and public health outcomes creates complex policy optimization problems that require careful consideration of feedback effects, distributional consequences, and the interaction between health and non-health policy instruments [33]. Our analysis reveals that conventional approaches to policy evaluation that treat health and economic outcomes as separable may significantly underestimate the true welfare effects of policy interventions and lead to suboptimal policy design.

The welfare analysis framework must account for both the direct utility effects of health improvements and the indirect effects operating through productivity and economic growth channels. The social welfare function $W = \int_0^1 U_i(C_i, H_i)di$ captures individual utility across the population distribution, but the general equilibrium effects of policy interventions create spillovers that affect the entire distribution of outcomes. A comprehensive welfare analysis requires solving for the equilibrium responses of all economic agents to policy changes and evaluating the net effects on social welfare.

In closed economies, the tight resource constraints create particularly strong trade-offs between different policy objectives [34]. Health policy interventions that require significant public resources must compete with other government expenditures and may necessitate higher taxes or reduced spending in other areas. The marginal cost of public funds in closed economies tends to be higher due to the limited ability to finance expenditures through external borrowing, making it crucial to ensure that health interventions generate benefits that exceed their opportunity costs.

The optimal health policy mix in closed economies emphasizes prevention over treatment due to the higher cost-effectiveness of preventive interventions and their greater potential for generating positive externalities. Public health measures such as vaccination programs, sanitation infrastructure, and health education can generate substantial population health improvements at relatively low cost, while also creating positive spillovers through reduced disease transmission and improved productivity. [35]

However, the political economy constraints in closed economies may limit the feasibility of optimal health policies. The benefits of preventive health interventions often accrue over long time horizons and may not be fully visible to voters, creating incentives for politicians to favor more visible but potentially less cost-effective curative interventions. The design of health policy institutions must account for these political economy factors to ensure that efficient policies can be implemented and sustained.

Open economies face different optimization problems due to their access to external resources and exposure to international competitive pressures. The availability of external financing relaxes resource constraints and allows for more ambitious health policy interventions, but also creates sustainability concerns if external financing proves temporary or conditional [36]. The optimal health policy strategy in open economies must balance the benefits of leveraging external resources against the risks of external dependence.

The international competitive dimension introduces additional considerations for health policy in open economies. Investments in population health can enhance international competitiveness by improving workforce productivity and reducing the costs of doing business, justifying higher levels of health spending from a growth perspective. However, if health improvements lead to higher wages without corresponding productivity gains, they may undermine export competitiveness and economic growth. [37]

The tax policy implications of health-economy interactions are particularly complex in open economies due to factor mobility considerations. Higher taxes to finance health spending may lead to capital flight and brain drain that partially offset the benefits of health investments. The optimal tax structure must account for these mobility responses and may require greater reliance on taxes on immobile factors such as land and natural resources.

International coordination of health policies emerges as an important consideration in open economies due to the cross-border spillovers of health outcomes [38]. Disease control measures, pharmaceutical regulations, and health system standards can have significant effects on trading partners, creating potential gains from policy coordination. However, the public goods nature of many health interventions creates free-rider problems that may limit voluntary cooperation.

The social insurance implications of health-economy interactions require careful consideration of risk-sharing mechanisms and their interaction with international markets. In closed economies, health insurance must rely entirely on domestic risk pooling, limiting the ability to smooth large health shocks. Open economies can potentially access international insurance markets, but may face moral hazard problems if external insurance reduces incentives for domestic health investments. [39]

The distributional consequences of health policies differ systematically between closed and open economies. In closed economies, health improvements that enhance productivity generate benefits that are shared relatively broadly through general equilibrium effects on wages and prices. In open economies, the benefits may be more concentrated among internationally mobile factors, potentially exacerbating inequality if the gains from trade are not distributed equitably.

The optimal timing of health policy interventions depends critically on the economic structure and development stage [40]. In early stages of development, basic public health measures generate the highest returns and should

be prioritized. As economies develop and integrate into global markets, more sophisticated health interventions become feasible and optimal. The sequencing of health policies must account for complementarities with other policy reforms and the evolution of institutional capacity.

The evaluation of health policy effectiveness requires accounting for general equilibrium effects that may not be apparent in partial equilibrium analysis. Health interventions that appear cost-effective in isolation may generate negative spillovers through their effects on other sectors or may crowd out private health investments [41]. Conversely, interventions that appear expensive may generate positive spillovers that justify their costs from a social perspective.

The interaction between health policies and macroeconomic stabilization policies creates additional complexity for policy optimization. Countercyclical health spending can help stabilize the economy during downturns by maintaining aggregate demand and preventing deterioration in human capital. However, the fiscal costs of such policies may conflict with deficit reduction objectives and may not be sustainable in countries with limited fiscal space. [42]

The role of international organizations and development assistance in health policy creates both opportunities and challenges for optimal policy design. External financing can enable countries to implement health interventions that would not be feasible with domestic resources alone, but may also create aid dependency and distort domestic policy priorities. The design of aid programs must account for these incentive effects and promote sustainable health system development.

7 Robustness Analysis and Sensitivity Testing

The complexity of the relationships between macroeconomic performance and public health outcomes necessitates extensive robustness analysis to ensure that our conclusions are not dependent on specific modeling assumptions, sample selections, or estimation methodologies. Our comprehensive sensitivity testing approach examines the stability of results across multiple dimensions, including alternative model specifications, different time periods, varying country samples, and alternative measurement approaches for key variables. [43]

The baseline empirical results demonstrate statistically significant bidirectional relationships between health and economic outcomes in both closed and open economy contexts, with effect sizes that are economically meaningful and consistent with theoretical predictions. However, the magnitude and significance of these relationships exhibit some sensitivity to specification choices, particularly in the treatment of dynamic effects and the inclusion of control variables.

Alternative instrument sets produce qualitatively similar results but with some variation in the magnitude of estimated effects. When we employ geographic and climatic instruments exclusively, the estimated impact of health outcomes on economic performance is somewhat larger than when we include institutional and policy instruments [44]. This pattern suggests that the institutional instruments may be capturing some of the channels through which health affects economic outcomes, leading to a more conservative estimate of the direct causal effect.

The temporal stability of the estimated relationships shows some variation across different time periods, with stronger health-economy linkages observed during periods of economic crisis and institutional reform. This pattern is consistent with the theoretical prediction that these relationships become more important when countries face binding resource constraints or undergo structural changes that alter the production function.

Subsample analysis reveals important heterogeneity in health-economy relationships across different regions and development levels [45]. Low-income countries exhibit stronger relationships between health and economic outcomes, consistent with the greater importance of basic health improvements for productivity in early stages of development. Middle-income countries show more complex patterns with significant variation depending on their degree of economic openness and institutional quality.

The measurement of economic openness presents particular challenges for robustness analysis, as different openness measures capture different aspects of international integration. Trade openness measures based on export and import shares produce somewhat different results than financial openness measures based on capital account restrictions. The most robust results are obtained when multiple openness measures are combined into composite indices that capture the multidimensional nature of economic integration. [46]

Alternative functional form specifications provide important insights into the nature of health-economy relationships. Linear specifications tend to underestimate the strength of these relationships compared to log-linear or flexible polynomial specifications. Threshold models reveal evidence of non-linear effects, with particularly strong relationships observed at low levels of health and economic development. These non-linearities have important implications for policy effectiveness and suggest that the returns to health investments may be highest in the poorest countries. [47]

The treatment of outliers and influential observations affects some results, particularly for small country samples. The exclusion of countries experiencing major conflicts, natural disasters, or economic crises reduces the estimated

volatility of health-economy relationships but does not substantially alter the average effects. This pattern suggests that extreme events amplify underlying relationships rather than creating spurious correlations.

Panel data estimation techniques produce more consistent results than cross-sectional approaches, highlighting the importance of controlling for unobserved heterogeneity in health-economy relationships. Fixed effects estimators yield smaller coefficient estimates than random effects approaches, suggesting that failure to control for unobserved country characteristics leads to overestimation of causal effects [48]. However, the inclusion of time trends and time-varying control variables reduces this bias substantially.

The choice of health outcome measures affects results in predictable ways. Mortality-based indicators tend to produce stronger relationships with economic outcomes than morbidity-based measures, likely reflecting the greater economic consequences of death compared to illness. Aggregate health measures that combine multiple indicators tend to produce more stable results than single-indicator approaches, though they may obscure important heterogeneity in the relationships for specific health conditions. [49]

Monte Carlo simulation exercises based on our theoretical model confirm that the instrumental variable estimators perform well under the assumed data generating process, with minimal bias and good coverage properties for confidence intervals. However, the simulations also reveal that weak instrument problems can lead to substantial bias when the correlation between instruments and endogenous variables falls below standard thresholds. This finding emphasizes the importance of instrument relevance testing in our empirical application.

The sensitivity to different lag structures reveals important dynamics in health-economy relationships. Short-run effects tend to be smaller and less precisely estimated than long-run effects, consistent with the gradual nature of health capital accumulation and the time required for health improvements to translate into productivity gains [50]. Dynamic specifications that allow for distributed lag effects produce more plausible estimates than static models, though they also reduce precision due to multicollinearity concerns.

Bootstrap confidence intervals provide additional evidence on the stability of our results, with relatively tight intervals around point estimates for most specifications. However, some results show wider confidence intervals when accounting for clustering at the regional level or when using block bootstrap procedures that preserve serial correlation structure. These wider intervals suggest greater uncertainty in the estimates than conventional standard errors might indicate. [51]

Cross-validation exercises demonstrate that our model specifications have reasonable out-of-sample prediction performance, with prediction errors that are comparable to or smaller than those from alternative approaches. The predictive performance is particularly good for one-step-ahead forecasts but deteriorates for longer forecast horizons, consistent with the difficulty of predicting health and economic outcomes over extended periods.

Placebo tests using randomly generated variables confirm that our instrument sets do not produce spurious relationships. When we replace actual health or economic outcomes with random variables, the instrumental variable estimators correctly find no significant effects, providing confidence that our identification strategy is capturing genuine causal relationships rather than statistical artifacts. [52]

Alternative country classification schemes for distinguishing closed and open economies produce generally consistent results, though with some sensitivity at the margins. Countries with intermediate levels of openness show mixed patterns that depend on the specific openness criteria used. This sensitivity highlights the gradual nature of economic integration and suggests that the closed-open economy distinction should be viewed as a continuum rather than a binary classification.

8 Discussion

The comprehensive analysis presented in this paper provides substantial evidence for the existence of significant endogenous relationships between macroeconomic performance and public health outcomes, while revealing important heterogeneity in these relationships across different economic structures and development contexts. The findings have significant implications for both theoretical understanding of health-economy interactions and practical policy design in an increasingly interconnected global economy. [53]

The theoretical framework developed in this study successfully captures the key features of health-economy relationships observed in the data, including the bidirectional causality, the role of institutional mediating factors, and the differential patterns between closed and open economies. The mathematical modeling approach provides a coherent foundation for understanding these complex interactions and offers a platform for conducting policy counterfactuals and welfare analysis.

However, several important limitations of the current analysis point toward promising directions for future research. The assumption of representative agent behavior, while analytically convenient, abstracts from important heterogeneity in health-economy relationships across different population groups [54]. Future research should incorporate distributional considerations more explicitly, examining how health-economy interactions differ across income, education, and demographic groups.

The treatment of technological change in our model, while more sophisticated than in previous studies, still relies on relatively simple assumptions about the health-technology relationship. The rapid pace of medical innovation and the increasing importance of digital health technologies suggest that future research should devote greater attention to modeling the specific mechanisms through which technological progress affects health outcomes and their economic consequences.

The international dimensions of health-economy relationships deserve additional attention, particularly in light of recent global health crises that have highlighted the interconnected nature of health and economic systems across countries. Future research should examine the role of international health cooperation, cross-border health spillovers, and the optimal design of global health governance mechanisms. [55]

The environmental health dimensions of economic development represent another important area for future investigation. Climate change, environmental degradation, and resource depletion create new challenges for maintaining health outcomes while pursuing economic growth objectives. The integration of environmental factors into health-economy models represents a crucial frontier for research and policy analysis.

The measurement challenges identified in this study point toward the need for continued investment in health data systems and the development of new indicators that better capture the multidimensional nature of health outcomes [56]. The increasing availability of administrative data, mobile health technologies, and remote sensing capabilities offers new opportunities for improving the measurement of health outcomes and their economic determinants.

The policy implications of this research extend beyond health policy to encompass broader questions of development strategy and institutional design. The finding that health-economy relationships are mediated by institutional quality suggests that governance reforms may be necessary complements to health and economic policies. Future research should examine the specific institutional mechanisms that facilitate positive health-economy interactions and the political economy factors that support or undermine these institutions.

The financial dimensions of health-economy relationships warrant additional investigation, particularly in light of the growing importance of health insurance markets and the increasing costs of medical technologies [57]. The interaction between health financing mechanisms and macroeconomic stability represents an important area for future research, especially in countries experiencing rapid epidemiological transitions.

The role of behavioral factors in mediating health-economy relationships represents another promising research direction. Individual decision-making regarding health investments, risk-taking behavior, and lifestyle choices may respond systematically to economic conditions in ways that amplify or dampen the aggregate relationships examined in this study. The integration of behavioral economics insights into health-economy modeling could provide important new perspectives on these relationships. [58]

The temporal aspects of health-economy interactions deserve continued attention, particularly the long-term consequences of health investments and the persistence of health shocks. The development of longer time series data and improved methods for analyzing long-run relationships could provide valuable insights into the sustainability of health improvements and their economic benefits.

The spatial dimensions of health-economy relationships represent an increasingly important research frontier as urbanization and migration patterns create new configurations of health risks and economic opportunities. The examination of health-economy interactions at subnational levels could provide insights into the mechanisms underlying aggregate relationships and inform more targeted policy interventions. [59]

The gender dimensions of health-economy relationships have been relatively underexplored despite clear evidence of differential health outcomes and economic participation patterns between men and women. Future research should examine how health-economy interactions differ by gender and how policies can be designed to address these differences effectively.

The application of machine learning and artificial intelligence techniques to health-economy research represents an exciting frontier that could provide new insights into complex non-linear relationships and interaction effects. These methods could be particularly valuable for identifying heterogeneous treatment effects and optimizing policy interventions across different contexts.

9 Conclusion

This comprehensive examination of the endogenous relationship between macroeconomic performance and public health outcomes reveals the complex and multifaceted nature of these interactions, while demonstrating significant differences in their manifestation across closed and open economy contexts [60]. The theoretical framework developed in this study provides a coherent foundation for understanding these relationships and offers important insights for policy design and institutional development.

The mathematical modeling approach successfully captures the key features of health-economy interactions, including bidirectional causality, dynamic feedback effects, and the mediating role of institutional factors. The distinction between closed and open economies emerges as a critical factor that fundamentally alters the transmission

mechanisms, volatility patterns, and policy effectiveness in these relationships. Open economies benefit from access to external resources and technology transfer that can enhance health outcomes, but also face greater exposure to external volatility and contagion effects. [61]

The empirical analysis provides robust evidence for the existence of significant endogenous relationships between health and economic outcomes, with effect sizes that are economically meaningful and stable across alternative specifications and estimation approaches. The instrumental variable strategy successfully addresses the simultaneity problems that have plagued previous research in this area, while the panel data approach controls for unobserved heterogeneity that could bias cross-sectional estimates.

The policy implications of this research are substantial and multifaceted. In closed economies, the tight resource constraints and strong feedback effects require careful coordination between health and macroeconomic policies, with emphasis on cost-effective preventive interventions that generate positive externalities. Open economies have greater policy flexibility due to access to external resources, but must balance the benefits of international integration against the risks of external dependence and volatility. [62]

The welfare analysis reveals that conventional approaches to policy evaluation may significantly underestimate the true benefits of health interventions by failing to account for general equilibrium effects and feedback mechanisms. The optimal policy mix depends critically on the economic structure, development stage, and institutional capacity, requiring context-specific approaches rather than universal prescriptions.

The robustness analysis confirms that the main findings are stable across alternative specifications, time periods, and country samples, though some sensitivity exists around the margins. The non-linear nature of health-economy relationships suggests that the returns to health investments may be highest in the poorest countries, with important implications for development policy and international assistance. [63]

Several important limitations point toward promising directions for future research, including the incorporation of distributional considerations, environmental factors, and behavioral mechanisms into health-economy models. The rapid pace of technological change in healthcare and the increasing importance of global health challenges create new research opportunities and policy challenges that will require continued theoretical and empirical investigation.

The findings of this study contribute to the growing literature on health economics by providing a unified theoretical framework that reconciles apparent contradictions in empirical findings across different contexts. The recognition of endogeneity in health-economy relationships has important implications for research methodology and suggests that previous studies may have systematically underestimated the true causal effects.

From a policy perspective, the results emphasize the importance of viewing health and economic policies as complementary rather than competing objectives [64]. The positive feedback effects between health improvements and economic growth suggest that well-designed health investments can be self-financing over the long term, while the negative consequences of health deterioration can create vicious cycles that undermine both health and economic objectives.

The international dimensions of these relationships highlight the need for coordinated approaches to health and economic policy in an increasingly interconnected world. The spillover effects of health outcomes across borders create both opportunities for mutual benefit and risks of contagion that require collective action and international cooperation.

The institutional mediating factors identified in this study point toward the crucial importance of governance quality and institutional capacity for realizing the potential benefits of health-economy interactions [65]. Investments in institutional development may be necessary complements to health and economic policies, particularly in developing countries where institutional weaknesses may limit the effectiveness of policy interventions.

The evidence presented in this paper supports a more integrated approach to health and economic policy that recognizes their fundamental interdependence and designs interventions to maximize synergies between health and economic objectives. This approach requires new forms of policy coordination, institutional arrangements, and evaluation methods that can capture the full range of benefits from integrated health-economy strategies.

As countries face new challenges from aging populations, epidemiological transitions, technological disruption, and environmental change, understanding the endogenous relationships between health and economic outcomes becomes increasingly critical for designing effective policy responses. The framework developed in this study provides a foundation for addressing these challenges and offers a roadmap for future research and policy development in this vital area. [66]

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